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A Heuristic Assessment Framework for the Design of Self-Regulated Learning Technologies

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Abstract
Researchers and educators have developed a variety of computer-based technologies intended to facilitate self-regulated learning (SRL), which refers to iterative learning processes wherein individuals set plans and goals, complete tasks, monitor their progress and outcomes, and adapt future efforts. This paper draws upon the SRL literature and related work to articulate two fundamental principles for designing SRL-promoting technologies: the Platform Principle and the Support Principle. The Platform Principle states that SRL-promoting technologies must incorporate clear platforms (i.e., tools and features) for engaging in planning, enacting, monitoring, and adapting. The Support Principle states that SRL-promoting technologies must include clear scaffolds for strategies, metacognition, motivation, and independence. These principles can be applied heuristically to formatively assess how and whether given learning technologies enable and scaffold self-regulation. More broadly, these assessments can empower educational technology creators and users to strategically design, communicate, and study technologies aligned with self-regulation. An exemplar application of the framework is presented using the PERvasive Learning System (PERLS) mobile SRL technology.

Keywords Educational technology · Heuristic assessment · Self-regulated learning

Self-regulated learning (SRL) describes iterative learning processes in which individuals set plans and goals, complete tasks, monitor their progress and outcomes, and adapt future efforts (Azevedo, 2009; Butler & Winne, 1995; Greene & Azevedo, 2007; Panadero, 2017; Pintrich, 2004; Winne, 2018). Across a truly vast body of literature, these highly metacognitive and self-directed activities have been credited as key contributors to success in *K-12 education* (Ben-Eliyahu & Linnenbrink-Garcia, 2015; Cleary & Kitsantas, 2017; Dent & Koenka, 2016; Kitsantas et al., 2009), *higher education* (Ben-Eliyahu & Linnenbrink-Garcia, 2015; Greene et al., 2010; Mega et al., 2014), *online learning* (Broadbent & Poon, 2015; Kizilcec et al., 2017; Littlejohn et al., 2016; Wan et al., 2012; Wong et al., 2019), and *workplace learning* (Margaryan et al., 2013; Siadaty et al., 2016; Sitzmann & Ely, 2011; Wan et al., 2012).

To promote effective SRL, researchers and educators have developed computer-based technologies that teach SRL strategies or provide a platform for self-regulation (Azevedo, 2005; Devolder et al., 2012; Winters et al., 2008), such as *MetaTutor* (Taub et al., 2021; Trevors et al., 2014), *gStudy* (Hadwin et al., 2010; Winne et al., 2010), and *Help Tutor* (Aleven et al., 2016; Roll et al., 2014). Many technologies now also track inputs and performance to offer individualized guidance and feedback (Roll & Winne, 2015; Tabuenca et al., 2015; Taub et al., 2021; Winne, 2019), and these tools are increasingly mobile—leveraging portable devices to enable SRL anywhere and "on the go" (Sha et al., 2012; Sharples, 2000; Tabuenca et al., 2015).

Crucially, the effectiveness of any SRL-promoting technology relies on quality design (Roscoe et al., 2017; Winters et al., 2008). Systems must adhere to defensible principles of instructional design and user-centered design (Kortum & Sorber, 2015; Zhang & Adipat, 2005), and several scholars have adapted usability assessments for e-learning (Mehlenbacher et al., 2005; Reeve et al., 2007; Zaharias & Koutsabasis, 2012). For instance, researchers have expanded Nielsen's (Nielsen & Budiu, 2013)

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heuristics (e.g., visible system status and real-world congruence) to incorporate instructional design concepts (e.g., use of prior knowledge and examples) (Zaharias & Koutsabasis, 2012) and instructor roles (Nacu et al., 2018).

To facilitate the design of SRL-promoting technologies, this paper articulates and demonstrates a concrete *heuristic assessment framework*. Our overarching goal is to empower developers to formatively assess technologies and implement design choices that align with the principles of SRL. The framework may also facilitate communication about and comparisons of different technologies by offering common language along with a structured way to characterize system features. To develop this framework, we draw upon the SRL literature to define two broad design principles for self-regulated learning technologies: the *Platform Principle* and the *Support Principle*. We then discuss how heuristic assessment can examine whether and how these principles are met by a technology. Finally, this framework is demonstrated via an analysis of the original PERvasive Learning System (PERLS) offered by the Advanced Distributed Learning (ADL) Initiative (Freed et al., 2014, 2017a, b, 2018; Suvorov, 2017).

Design Principles for Self-Regulated Learning Technologies

Overview of Self-Regulated Learning

SRL has been characterized in diverse ways but unifying themes have emerged (Panadero, 2017). First, SRL typically occurs across several iterative "phases" of activities—such as planning, enacting, monitoring, and adapting—and successful coordination of these phases requires strategies and strategy knowledge. Progress through the phases can be nonlinear, and the inputs and products of each phase can influence each other. Second, external supports are often necessary to promote SRL. Although SRL is ideally *self*-directed, the reality is that assistance from others (or from software systems) is needed to initiate or maintain effective self-regulation. In the following sections, we further describe these broad phases of SRL along with the role of strategies and scaffolding, from which emerge two design principles.

Phases of Self-Regulated Learning

Conceptualizations of SRL describe "phases" of learning activities that unfold iteratively, interdependently, and recursively. Progress through the phases is not necessarily linear, and the inputs and products of each phase can influence each other via feedback and feed-forward mechanisms. Likewise, learners do not simply move through the phases until learning is "complete" but may revisit phases repeatedly as they gain mastery. Thus, the terminology of "phases" is a misnomer yet useful for specifying collections of dynamic processes that may be enabled by SRL technologies. The exact number and nomenclature of phases differ across theoretical frameworks. In this paper, we describe a four-phase model that comprises planning, enacting, monitoring, and adapting.

In a *planning* phase, learners analyze and define tasks, review instructions, gather resources, choose strategies, set goals, and establish assessment or evaluation criteria (Eilam & Aharon, 2003; Kostons et al., 2012; McCardle et al., 2017). For instance, planning can involve judging time constraints, scheduling tasks, and other time management activities (Dunlosky & Ariel, 2011; Hartwig & Dunlosky, 2012; Rodriguez et al., 2018). Relevant learning and performance strategies can be honed in advance to avoid later trial-and-error, and plans can prepare learners to attend to signals of success (Panadero & Romero, 2014; Panadero et al., 2017) while crafting contingency plans for when errors or obstacles arise.

In an *enacting* phase, learners attempt to complete (or make progress on) their tasks, which may require demonstrating knowledge, acquiring new knowledge, solving problems, making decisions, and more. To do so, learners engage in diverse activities, such as reading and comprehending text (McNamara, 2017), searching for information (Walraven et al., 2013), and solving problems (van Gog et al., 2020). In this stage, learners also enact their plans. Consequently, learners who lack clear plans are disadvantaged because they have less direction, fewer steps to follow, and may be unprepared to detect errors.

In a *monitoring* phase, learners assess their own knowledge and performance, judge outcomes and products, predict future outcomes, and diagnose mistakes (Deekens et al., 2018; Kostons et al., 2012). These judgments can be prospective, concurrent, or retrospective, and may occur at any time throughout the process (Baars et al., 2014; Mihalca et al., 2017). For instance, before solving a problem, learners might retrospectively reflect on prior problems and make prospective predictions about upcoming tasks. As students work, they can determine how well they are doing. Finally, after generating a solution, students might retrospectively assess accuracy and diagnose incorrect answers. Such self-assessments are essential because learning and task performance rarely unfold smoothly (Bjork et al., 2013; Panadero et al., 2017). Mistakes can halt further progress and lead to poor solutions, harmful decisions, or misconceptions.

In a "final" *adapting* phase, learners "close the loop." Ideally, self-monitoring activities reveal learners' successes and failures, strengths and weaknesses, knowledge gains and gaps, and other needs. A core assumption of SRL is that self-regulated learners use this information to adapt and improve.

For example, if learners realize that they are missing critical knowledge, they take action to fill that knowledge gap, such as searching online for more information (Walraven et al., 2013) or seeking help (Aleven et al., 2016). Similarly, if learners realize that their goals were too ambitious, they might pivot to better leverage resources or abilities. Any aspect of planning, enacting, or monitoring is potentially subject to inspection and change.

Strategies and Self-Regulated Learning

As previously suggested, strategies and strategy knowledge are fundamental to SRL—they provide specific operations that learners can employ to accomplish each phase. In brief, strategies are step-by-step procedures that are purposefully implemented to achieve target outcomes, improve performance, optimize resource use, and overcome hurdles (Alexander et al., 1998; Broadbent & Poon, 2015; Donker et al., 2014). Successful performance of most tasks is facilitated by general and task-specific strategies that impose structure, guide attention, promote deeper reasoning, or otherwise improve accuracy and efficiency. Strategies often require more work than the minimum needed for the task, but this extra effort often results in better outcomes (Winne, 2018).

In addition to strategies for enacting tasks, SRL activities and phases themselves may also be approached strategically. For example, planning involves assessing time constraints and scheduling tasks. Thus, self-regulation may benefit from time management strategies (Dunlosky & Ariel, 2011; Hartwig & Dunlosky, 2012; Rodriguez et al., 2018). Similarly, self-questioning strategies (Joseph et al., 2016) and self-testing strategies (Hartwig & Dunlosky, 2012; Rodriguez et al., 2018) can enhance self-monitoring and self-assessment. Students also have a variety of methods available to overcome obstacles, such as information-seeking (Walraven et al., 2013) and help-seeking (Roll et al., 2014). Many regulatory strategies thus serve a dual purpose, such as using self-questioning to both facilitate *and* monitor text comprehension (Joseph et al., 2016; Snow et al., 2016).

Scaffolding Self-Regulated Learning

Ample research has also revealed numerous constraints that can hinder effective SRL (Aleven et al., 2016; Azevedo et al., 2008; Bjork et al., 2013; van Meeuwen et al., 2018; Zheng, 2016). Although SRL is "self" driven by definition, learners often need external guidance, feedback, and encouragement to acquire SRL proficiency (Azevedo et al., 2008; Cleary & Kitsantas, 2017; Devolder et al., 2012; Dignath & Büttner, 2008; Lee et al., 2010; Nicol & Macfarlane-Dick, 2006; Zheng, 2016). For instance, many learners lack skill in metacognition and self-monitoring. Learners may fail to assess themselves or may be poorly calibrated in estimating their performance (Alexander, 2013; Azevedo, 2009; Dunlosky & Thiede, 2013). In addition, learners may rely on misleading cues to judge their recall or understanding (Bjork et al., 2013). Numerous links between SRL motivation and affect have also been observed (Cleary & Kitsantas, 2017; Duffy & Azevedo, 2015; Littlejohn et al., 2016; Mega et al., 2014; Pintrich, 2004; Smit et al., 2017), showing that learners with lower intrinsic motivation or lower self-efficacy are less likely to engage in SRL.

Fortunately, effective scaffolding for SRL can take many forms, such as instruction, prompting, feedback, and assessment. The exact manifestation of the scaffolds is likely less important than whether scaffolding is provided—partial support is better than no support, and combining multiple scaffolds may be ideal. For instance, many learners benefit from direct instruction about SRL and relevant strategies (e.g., techniques for setting reasonable goals) and opportunities to practice these skills. Direct and indirect prompts can remind learners about what they should (or could) do, guide them toward optimal actions, and draw attention to important ideas and tools (Bannert et al., 2015; Berthold et al., 2007; Devolder et al., 2012; Müller & Seufert, 2018).

Another approach is to provide feedback in response to learners' inputs, behaviors, or performance (Azevedo et al., 2008; Lee et al., 2010; Nicol & Macfarlane-Dick, 2006; Roll et al., 2014; Shute, 2008). Summative feedback provides objective indicators of performance (e.g., correct vs. incorrect) whereas formative feedback offers information on how to improve. Because students' are not always skilled at self-monitoring, external feedback can reduce the mental workload of identifying knowledge gaps, strengths and weaknesses, and so on. Feedback can also convey missing or new information, introduce or refine strategies, and guide students' through successful self-regulation.

Self-assessment and formative assessment resources (e.g., rubrics and peers) can further facilitate strategies, self-monitoring, and learning (Panadero & Romero, 2014; Panadero et al., 2017). Learners can use rubrics to inspect assessment criteria and exemplars, which makes these guidelines more accessible and usable. Learners can also participate in creating these rubrics (Fraile et al., 2017), which further promotes self-monitoring, self-efficacy, and planning. Relatedly, learning analytics and automated assessment tools are increasingly using student data to personalize recommendations and feedback (Azevedo & Gašević, 2019; Gašević et al., 2017; Lodge et al., 2018; Roll & Winne, 2015; Tabuenca et al., 2015; Winne, 2018; Winne & Baker, 2013). Learners' actions (e.g., navigation) and inputs (e.g., short-answer responses) can be analyzed by the software, and algorithms can guide responding to students' knowledge, skills, and cognitive-affective states in real-time. Similarly, these data can be communicated to students via feedback and visualizations to help them monitor their performance and adapt.

A final consideration is that scaffolding, although necessary, should not be permanent. If the goal is to promote *self*-regulation, then external software tools cannot scaffold learners in perpetuity. In educational research, "fading" refers to the gradual and adaptive removal of support until learners can perform tasks on their own (Azevedo & Hadwin, 2005; Belland, 2014; Devolder et al., 2012). Importantly, fading does not necessarily require the removal of *all* assistance, but learners should not need to be (re)taught strategies repeatedly, prompted to self-monitor on every problem-solving step, or require constant encouragement.

Enabling and Scaffolding Strategic Self-Regulation

The vast literature on SRL has documented multiple clusters of strategic learning activities that contribute to successful learning. In addition, this research has described ways in which crucial aspects of SRL can (and perhaps should) be externally promoted. From this work, two broad principles emerge for the design of SRL-promoting technologies.

The Platform Principle

In the design of educational technologies, the *Platform Principle* states that *SRL-promoting technologies must incorporate clear platforms* (*i.e.*, *tools and features*) *for engaging in planning*, *enacting*, *monitoring*, *and adapting*. Technologies that seek to promote SRL must enable learners to engage in relevant processes via tools embedded in or provided by the software. For example, "creating a calendar" and "making to-do lists" are both planning strategies, and thus software might include "calendar tools" for learners to plan their studying or assignments, or "to-do list tools" for tracking completion. Similarly, software may offer direct access to subject matter content (e.g., e-textbooks) for students to read, along with "drawing" or "quiz" platforms for diagramming or self-assessment strategies.

There are countless ways to implement relevant platforms and we do not endorse any particular method. Similarly, it is an empirical question whether a technology must include platforms for *all* phases or whether certain phases are more crucial. However, we hypothesize that technologies that offer more and diverse platforms will be more effective than technologies that offer fewer platforms—a "fully-featured" SRL-promoting technology might allow learners to engage in all SRL phases (i.e., "close the loop") without ever exiting the system.

The Support Principle

In the design of computer-based learning environments, *the Support Principle states that SRL-promoting technologies must include clear scaffolds for strategies*, *metacognition*, *motivation*, *and independence*. These supports might take a variety of forms such as direct instruction, prompting, feedback, and assessments. As with platform design, we do not endorse any specific method. However, more robust systems will likely offer support for every included platform (i.e., if the technology includes notetaking tools, it should also include notetaking assistance), and might even have multiple forms of support (e.g., hints for notetaking strategies, prompts to take notes, and automated feedback on note quality). These supports should encourage learners to be proactive and independent, such as the option to deactivate hints, prompts, or feedback functions as learners become more self-directed.

Formative Assessment of SRL Technology Design

The dual demands imposed by the Platform Principle and Support Principle result in potentially complex system designs—there are myriad ways to implement SRL. When (re)designing, (re)developing, or even evaluating such systems, we propose that it is useful to employ a *heuristic assessment framework* to map out whether and how design principles are addressed.

Heuristic Assessment

Heuristic assessments are a mainstay of usability testing (Dumas & Fox, 2009; Kortum & Sorber, 2015; Zhang & Adipat, 2005). Usability can be defined as the extent to which products, devices, or systems can be learned and used by intended audiences to complete tasks with accuracy, ease, speed, and satisfaction (ISO 9241, ISO, 2018; Nielsen & Budiu, 2013). User testing often recruits end-users to complete tasks with prototypes and products while gathering data on completion, accuracy, attitudes, and interactions with the system. Informative usability assessments can also begin "in house" and early in the design process before end-users touch the system. Inspection methods such as *heuristic assessments* (Gómez et al., 2014; Hvannberg et al., 2007; Nielsen & Budiu, 2013; Zaharias & Koutsabasis, 2012) or *cognitive walkthroughs* (Huart et al., 2004; Karat et al., 1992; Khajouei et al., 2017; Mahatody et al., 2010; Polson et al., 1992) offer principled ways for developers to systematically inspect their own designs (e.g., wireframe mockups and prototypes) and identify threats to usability based on pre-defined parameters (see Khajouei et al., 2017).

The speed and low cost of heuristic assessment facilitates iteration, which allows usability threats to be mitigated before substantial time or money are invested. Indeed, heuristic assessments have contributed to improved STEM education (Minichello et al., 2018), digital textbooks (Lim et al., 2012), e-learning and online instruction for web-based writing courses (Miller-Cochran & Rodrigo, 2006), web-based tools for knowledge-sharing and collaboration (Hvannberg et al., 2007), web-based support for competence maps (Stoof et al., 2007), online employee training (Zaharias & Poylymenakou, 2009), MOOC-like online courses (Zaharias & Koutsabasis, 2012), virtual laboratories (Davids et al., 2013), game-based social skills training (Tan et al., 2013), peer communication (Carmichael & MacEachen, 2017), and educator roles (Nacu et al., 2018). These assessments uncovered superficial and substantive instructional design issues (e.g., access, navigation, locating resources, and clarity of instructions), which empowered the creators to reduce or prevent these problems in future studies and interventions.

Methodologically, the parameters considered in heuristic assessments can be established a priori based on knowledge of best practices and/or the features of specific tasks and domains. For instance, some researchers have begun with Nielsen and colleagues' classic heuristics (Nielsen & Budiu, 2013). By considering pedagogical and instructional concerns, these principles can be elaborated for learning contexts (Zaharias & Koutsabasis, 2012; Nacu et al, 2018; Reeves et al., 2007; Tan et al., 2013). For instance, one heuristic recommends using familiar symbols in interfaces that align with users' expectations. In a multimedia lesson, learners might expect "play" and "pause" navigation buttons common to many systems. However, in some cases, novel interfaces may be intentionally designed to transform students' behaviors, such as eliciting an unfamiliar learning activity (e.g., teaching a computer agent via concept-mapping; Roscoe et al., 2013). In these cases—where there is a discrepancy between interface expectations and instructional activities—new concepts, interfaces, and controls must be explained to learners.

The heuristic assessment framework and parameters specified by the Platform Principle and Support Principle should improve the quality of systems that support SRL. First, developers, researchers, and educators can assess whether platforms for planning, enacting, monitoring, or adapting are included (or not) in the technology. Documentation can then detail how platforms are implemented via system tools, functions, or features. Second, and similarly, assessors can consider whether each phase or platform is supported (or not) with regard to strategies, metacognition, motivation, or independence. The presence of scaffolds can be accompanied by details about implementation.

Notably, incorporating platforms and supports for all phases is not always feasible, and there is no justifiable demand that the system be the *sole* platform or source of support. Learning activities might also occur offline or use a separate technology (e.g., a chemistry simulation), and human instructors and peers can give instructions, discuss strategies, demonstrate methods, and provide feedback. However, any blend of "online" and "offline" SRL should be explicitly addressed by system documentation. Developers should make users aware of what the system offers regarding SRL and whether critical SRL needs must be met via other means.

Application of the Heuristic Assessment Framework: PERLS

Implementation of the framework is exemplified through an analysis of the prototype PERvasive Learning System (PERLS) Version 1.0 developed by SRI International for the Advanced Distributed Learning Initiative (ADL) of the US Department of Defense. This analysis was part of an effort to refine PERLS and transition it into the military learning ecosystem. The formative assessment proceeded in four stages:

- First, researchers collected and reviewed all available documentation pertaining to the PERLS V.1 system, including manuals, prior publications, and presentation slides. These materials explained the implementation and rationale of system features along with an underlying theoretically model that guided design.
- Second, the team accessed and explored the system itself to review existing functions, features, and interfaces. Researchers navigated through example learning content, courses, and assessments from the perspective of learners.
- Third, driven by the first two assessments, researchers systematically annotated examples and evidence regarding all assessment framework components and their implementation: platforms for SRL, supports for SRL, and specific manifestations of support (i.e., strategies, metacognition, motivation, and independence).
- Finally, framework components and interconnections were visualized to summarize how the system enabled various phases of self-regulation. Specifically, "box and arrows" diagrams depicted how individual features supported self-regulation behaviors and other functions (e.g., data from planning tools used to modify content recommendations).

Overview of PERLS and Underlying Self-Regulated Learning Model

PERLS was a mobile, personalized system for delivering content and recommendations to learners in the workplace or informal settings (). Specifically, learners could use a mobile device to access a variety of instructional "content cards" (e.g., text documents, videos, and web-based simulations) and "action cards" that enabled goal-setting and quizzes. Underlying these tools was a contextually aware recommender system that suggested learning objects based on the users' activity (e.g., topic access and navigation), location, and topic importance (Freed et al., 2018). Learners could use the system to acquire knowledge or skills in a selected domain while the software attempted to guide appropriate learning activities and trajectories. PERLS thus represented a fairly flexible SRL-promoting technology—a means for office workers or military servicepersons to enhance their education in a self-determined manner. In addition, PERLS was created to support SRL using functions, interfaces, and prompts to guide attention and interest. A handful of usability and pilot studies (Freed et al., 2014, 2017b, Suvorov, 2017) reported favorable perceptions of flexibility, portability, tracking, and motivation of the prototype system.

The aforementioned design of PERLS was guided by SRL-inspired theoretical model with three phases of "exploring," "studying," and "sharpening" (Freed et al., 2018). This model is visually summarized in Fig. 1.

The PERLS Explore phase (comprising Discovery, Dabbling, and Bridging activities) entailed gaining awareness and selecting topics for future study. Discovery was defined as seeking out new topics intentionally (e.g., web search) or incidentally while working on other tasks. Learners might then engage in Dabbling—low-effort review to build familiarity and form interests, such as skimming a website or watching a short video. Finally, bridging involved committing to further learning by assessing competence and understanding, formulating plans and goals for learning, and considering available time and resources.

Overall, this phase was aligned to the planning phase of SRL. In particular, "bridging" seemed to capture intentional planning, wherein learners analyze and define tasks, gather resources, set goals, and establish metrics. The concepts of "discovery" and "dabbling" incorporated initial exposure to the domain. Rather than assuming learners were already aware of relevant topics, the PERLS model acknowledged this introductory step. Developers also mentioned the need to address both intrinsic and extrinsic learning motivations for adult learners (Freed et al., 2014). However, the model might have connected to much stronger foundations for SRL and planning related to achievement goals (Bernacki et al., 2012; Duffy & Azevedo, 2015), self-assessment (Fraile et al., 2017; Panadero et al., 2017), or task selection (Kostons et al., 2012; Raaijmakers et al., 2018).

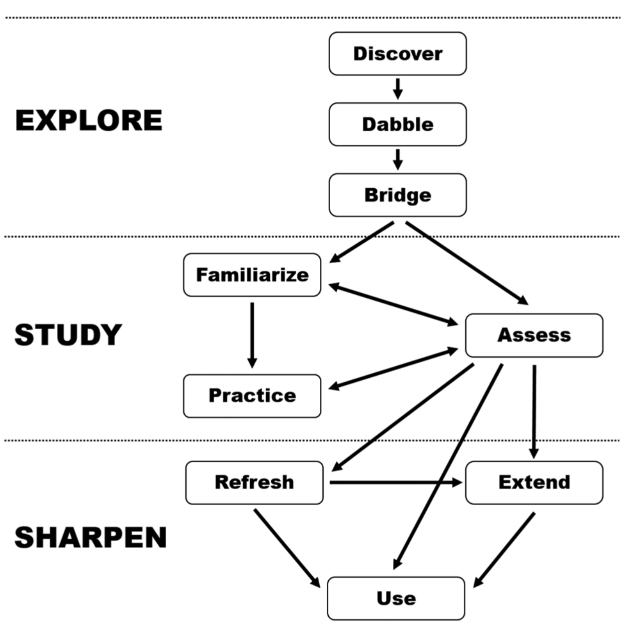

Fig. 1 PERLS self-regulated learning model

The PERLS study phase (comprising familiarize, practice, and assess activities) was defined as a period of completing courses, building competence, developing skills, or otherwise learning the material. In familiarize, learners reviewed materials to learn basic concepts, principles, and procedures. In practice, learners developed fluency in retrieving and applying both declarative and procedural knowledge. Throughout these activities, learners were believed to engage in assessing. Learners were assumed to use self-assessment or feedback to gauge progress, which ostensibly enabled "course corrections and adoption of new strategies to improve results [and] determine when the learner is ready for more advanced learning" (Freed et al., 2018, p. 4).

Overall, the study phase appeared to focus on enacting, but also incorporated elements of planning, monitoring, and adapting. Familiarization seemed similar to both "dabbling" and "bridging," and emphasized "introductory" studying. This aspect of the model possibly neglected SRL activities that are focused on advanced topics, deeper comprehension (Graesser et al., 2010; McNamara, 2017), critical thinking (Ghanizadeh, 2017), or transfer (Leberman et al., 2016; Zepeda et al., 2015). These forms of learning could potentially be represented under "practice" but insufficient detail was provided. The developers also appeared to describe deliberate practice but did not clearly connect to that research (Ericsson et al., 1993; Macnamara et al., 2014).

The inclusion of assessment was a strength but also demonstrated lack of specification for distinct processes. Feedback is a powerful resource for scaffolding SRL (Butler & Winne, 1995; Lee et al., 2010; Nicol & Macfarlane-Dick, 2006; Shute, 2008), yet the PERLS model did not seem to draw on that literature to inform feedback design. Similarly, the model did not specify the roles or timing of different metacognitive judgments (e.g., prospective vs. retrospective, Baars et al., 2014; Mihalca et al., 2017) nor distinguish between the effects of self- versus peer assessments (Panadero et al., 2016, 2017; Panadero & Romero, 2014). The mechanisms by which learners would use such information to refine future activities, plans, or strategies were also unclear.

The final phase of sharpen (comprising refresh, extend, and use activities) was defined as applying, maintaining, and building knowledge and skills. In refreshing, learners tried to reinforce their skills and knowledge. During extending, learners built upon existing knowledge or skills, perhaps developing greater proficiency than required for the tasks at hand. Finally, learners could use their knowledge to investigate or solve real-world problems and situations. The sharpen phase seemed to revisit the enacting phase but with a focus on elaboration and application rather than initial acquisition—elements that were missing from the study phase. This component of the model was perhaps the least specified. It remained unclear what strategies learners might use to improve retention or comprehension, such as returning to "familiarizing" and "practicing" or invoking new activities. "Extending" could encompass a variety of constructive or co-constructive learning activities (Chi & Wylie, 2014). However, developers did not connect their definitions of "extending" or "use" to existing theories of knowledge construction, transfer, creativity, or similar processes.

In sum, components of the PERLS SRL model exhibited plausible links to established SRL concepts but did not articulate these foundations in depth. Core assumptions were not strongly grounded in prior research or validation studies. Importantly, if a guiding model demonstrates gaps (e.g., lack of clear monitoring and adapting phases), then the resulting system itself might exhibit similar gaps (e.g., neglecting one or more platforms for SRL).

SRL Platforms and Supports in PERLS

PERLS design incorporated features for accessing learning materials, planning, quizzes, and recommendations. This heuristic assessment begins with the core PERLS content-delivery system and its role in the *enacting* phase of SRL. We then consider how and whether PERLS addresses *planning*, *monitoring*, and *adapting*.

Enacting Phase

PERLS design included a potentially powerful platform for enacting learning and related tasks. Using a "card-based" interface, learning objects were presented as various "content cards" in the form of expository texts, multimedia videos, recordings of interviews or demos, and more. Thus, learners could study in a variety of reading, listening, watching, and interactive modalities (E1 in Fig. 2). Content curators (e.g., instructors) could incorporate materials that ranged from quick "dabbling" videos to detailed materials for "practice" or "extending." Sets of related learning objects could be collected into "topics" (materials related to a similar theme) or "courses" (materials to be completed in a specific order).

Learning materials could be hosted internally on servers dedicated to a given PERLS deployment (e.g., military training resources). Importantly, PERLS could also interact with external resources in two ways (E2). First, content cards might link to external websites or mobile-enabled software. For instance, links might send learners to news sites or podcasts, thus enabling them to connect ideas learned in a PERLS course to current events. Second, learners could access other learning technologies such as simulations, intelligent tutoring systems, or games. Consequently, the library of resources available through PERLS users was potentially unlimited. Although external content was not managed by

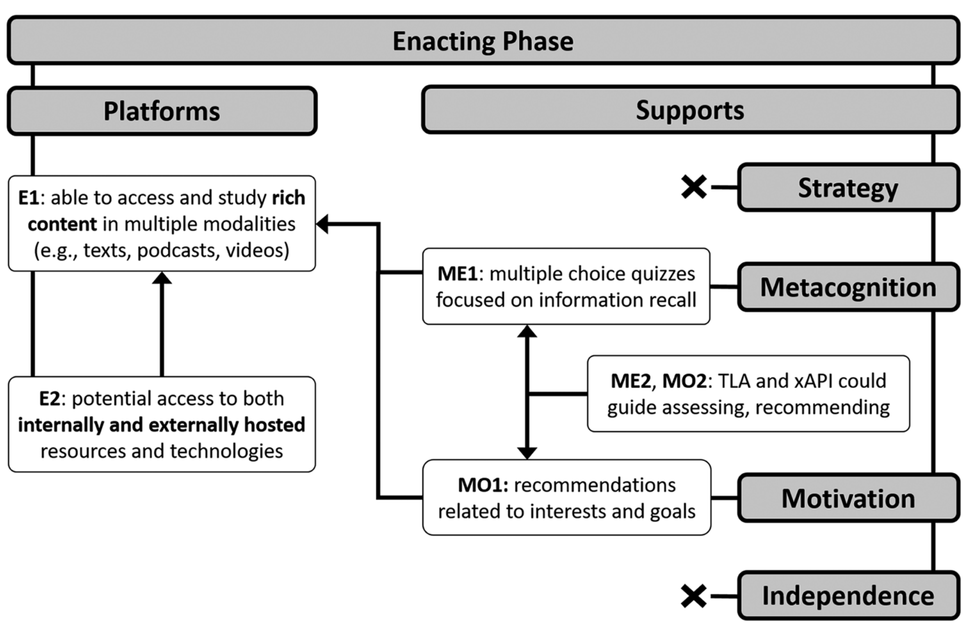

Fig. 2 Heuristic assessment of PERLS enacting phase. If present, labels denote enacting platforms (E) and support for strategies (ST), metacognition (ME), motivation (MO), or independence (IN)

PERLS curators, the system could potentially track learners' access of the relevant content cards.

Support for enacting was tenuous. PERLS offered no instruction or "action cards" for specific learning strategies, such as strategies for reading, integrating information across sources, learning with multimedia, or online information search. Thus, although PERLS could connect learners to vast resources, it was not clear how the system assisted learners in comprehension. Similarly, there was no clear support for independence. Indeed, the developers stated that "effective support technology must be engaging and habit-forming so that self-learners use it regularly during learning trajectories that can last months or years" (). Thus, rather than envisioning a future when learners no longer need PERLS, the intention appeared to be make PERLS a permanent resource. PERLS also offered weak metacognitive support via "quiz cards" that contained short multiple-choice quizzes (often only one question) to test retention (ME1). Thus, learners were partially supported in assessing shallow memory of facts rather than deeper metacognitive judgments of comprehension, knowledge gaps, memory, or other needs.

It is worth noting that the ability for PERLS to leverage external resources might offset some of the above critiques. Although PERLS may not teach learning strategies directly, learners could be connected to outside resources (e.g., websites or intelligent tutoring systems) that did cover these topics. Subsequently, when learners returned to their PERLS course(s), they would be better prepared to learn. In other words, what support that PERLS did not provide itself could be "outsourced" with careful collaboration and planning. Another potential strength of PERLS was its contextually aware recommendation functions, which offered motivational support by connecting learners with relevant, interesting, and important content (Freed et al., 2018) (MO1). Notably, it was not clear whether these features were functionally implemented within PERLS, but the design concept was well-aligned with the principle of motivational support. As outlined by Freed et al. (2018), the system might track learners' goals and interactions with learning objects (e.g., frequency) to estimate current interests, which in turn could prompt recommendations for related content. Additionally, PERLS design included "value propositions" that offered a rationale for accepting a recommendation—PERLS communicated "selling points" to nudge learners to access the recommended content. These selling points might be based on learners' interests, location (e.g., nearby landmarks), urgency (e.g., impending deadlines), or attitudes (e.g., preferences for challenge or social interaction).

Finally, later PERLS development considered both Total Learning Architecture (TLA) and Experience API (xAPI). TLA principles and specifications emphasize cross-platform interoperability and sharing of data on user and learner performance, behavior, and contexts across diverse systems and technologies (Folsom-Kovarik & Raybourn, 2016; Smith et al., 2018). xAPI uses human and machine-readable data to track key variables, which permits dynamic tracking across any platform or system that also use xAPI (e.g., Learning Management Systems, tutoring systems, wearables, and so on) (Alonso-Fernández et al., 2019; Sottilare et al., 2017). Thus, if PERLS was connected with other xAPI learning technologies, the systems could share information about users' actions and outcomes, which would in turn enable additional assessment (ME2) and personalization (MO2).) reported a demonstration of integration using PERLS and Perceptual Adaptive Learning Modules (PALMS) to train learners on pattern recognition tasks (e.g., recognizing anatomic structures). PALMS provided the content whereas PERLS provided additional learning materials, content, and coordination.

Planning (P) Phase

PERLS offered a platform for two aspects of planning: *topic selection* (P1 in Fig. 3) and *goal-setting* (P2). Learners could locate topics and courses via searching or recommendations, and then could choose which topics to pursue. For example, choosing the topic "Computing" might display options for websites with overviews of computing, short videos about augmented reality or conversation analysis, websites about cybersecurity, and so on. In a goal-setting interface, users had the option to "Set Learning Goal," such as the following prompts (Freed et al., 2014):

- "I want to Explore. Get a taste. Make a commitment."
- "I want to Study. Dig in. Work toward your goal."
- "I want to Master. Lay a foundation. Become an expert."
- "I want to Stay Sharp. Keep up to date. Build your expertise."

Selected goals refined the recommendations; choosing to "explore" resulted in shorter and less challenging topic recommendations, whereas "master" led to more advanced content.

The system offered several supports for strategic planning. First, all content cards included indicators for modality (e.g., audio, web, or document) and time (i.e., duration) (ST1). Learners could organize their learning activities based on preferences and available resources (e.g., listen to a podcast while commuting versus reviewing terminology prior to a meeting). However, these strategic decisions were largely left to the learners—the system did not include explicit guidance in *how* to plan well. Similarly, there was no calendar function for users to schedule activities. The recommendation system ostensibly facilitated planning by offering topics and activities that aligned with stated goals, interests, and SRL states (e.g., suggesting entertaining content when

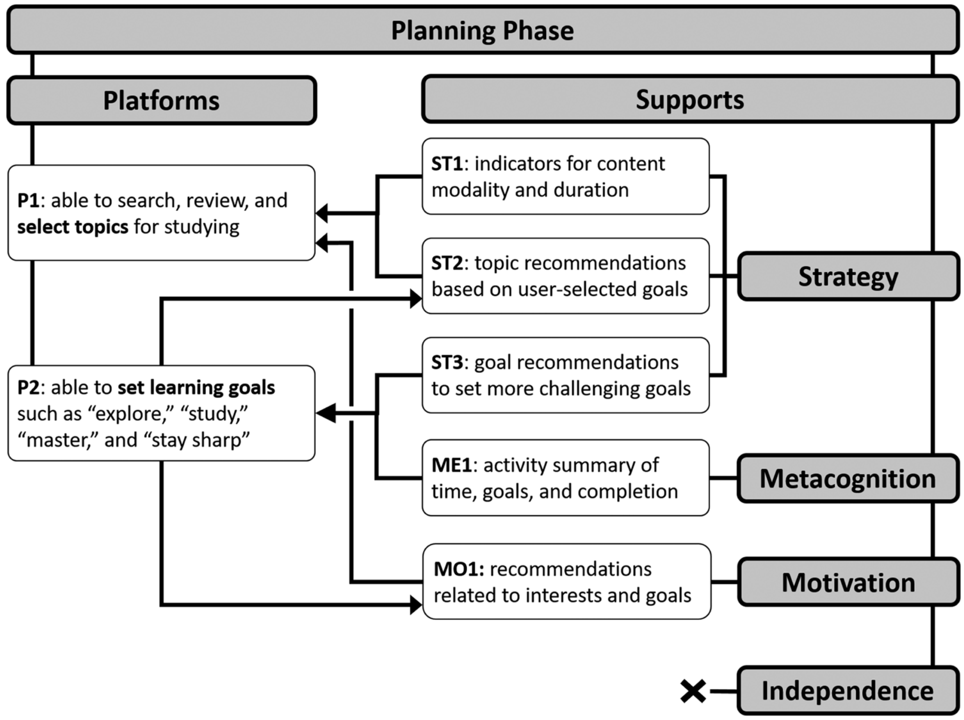

Fig. 3 Heuristic assessment of PERLS planning phase. If present, labels denote planning platforms (P) and support for strategies (ST), metacognition (ME), motivation (MO), or independence (IN)

learners are "dabbling") (ST2 and MO1). The system could also encourage learners to set more intensive learning goals (e.g., "master") after they gained familiarity with basic ideas (ST3). In this way, the recommender system might have encouraged learners to be more goal-oriented.

Metacognitive support for planning was superficial. Users could access an "Activity" summary that reported days and time spent learning, listed selected goals, and displayed completion progress (ME1). This information helped learners to track their plans and progress. However, metacognitively, there was no specific support for learners to assess the quality, feasibility, or relevance of their plans.

Monitoring (M) Phase

Although isolated metacognitive tools were provided for testing recall and recognition (i.e., single-item multiple-choice quizzes) and reviewing plans (i.e., activity reports), the broader monitoring phase of SRL was largely neglected in PERLS. Learners were assumed to monitor themselves periodically or accurately, but platforms within the system did not directly enable such work. For example, the system included no formal functions for conducting summative or formative assessments. Learners had no obvious means for gauging their understanding or performance across multiple topics, courses, or over time. PERLS also lacked features to prompt or motivate metacognitive predictions (e.g., "How much time will this take?"), self-monitoring (e.g., "Is anything about this topic confusing?"), or other reflections (e.g., "How will this information be useful in my career?"). Due to the sparse nature of this assessment, no summary figure is provided.

Adapting (A) Phase

A critical component of SRL is "closing the loop," which refers to using metacognitive judgments or external feedback to adapt existing plans, behaviors, criteria, and other learning processes. Such iteration was possible within PERLS if learners chose to do so spontaneously, but the system lacked clear platforms or supports for adapting. In practice, learners could delete or change their goals, abandon irrelevant lessons, select new lessons, and more. However, nothing in the system directed these activities as explicit attempts to self-regulate. Due to the sparse nature of this assessment, no summary figure is provided.

Summary

Driven by a plausible but underspecified learning model, the strongest feature of PERLS was perhaps its role as a gateway to a wealth of instructional materials. Whether hosted on a dedicated server or externally linked, learners could access diverse multimedia content or other software to acquire knowledge and skills. A self-regulated learner would likely find PERLS to be a useful resource. And, to enable and support such self-regulation, PERLS also included a platform for goal-setting along with functions for motivating learners

Table 1 Condensed summary matrix of PERLS heuristic assessment

	SRL phase			
	Planning (see Fig. 2)	**Enacting** (see Fig. 3)	**Monitoring**	**Adapting**
Platform	•**P1**: select topics •**P2**: goal-setting	•**E1**: rich content and modalities •**E2**: internal and external content	Not included	Not included
Strategy support	•**ST1**: info about modality, timing •**ST2**: recommend based on goals •**ST3**: encourage challenging goals	Not included	Not included	Not included
Metacognition support	•**ME1**: activity report summary	•**ME1**: multiple choice quizzes of retention •**ME2**: TLA and xAPI integration could guide assessment	Not included	Not included
Motivation support	•**MO1**: recommend based on interests and goals	•**MO1**: recommend learning topics based on interest, location, goals •**ME2**: TLA and xAPI integration could guide recommendations	Not included	Not included
Independence support	Not included	Not included	Not included	Not included

with recommendations. Based on our heuristic assessment framework, PERLS addressed planning and enacting phases of self-regulation. Additional support features (e.g., strategy instruction, prompting, feedback, and independence) would likely increase the potential effectiveness of these tools. However, platforms and support for monitoring and adapting were largely missing. Individuals who already possessed such skills could employ them, but PERLS did not explicitly or directly enable or scaffold them. Table 1 provides a condensed summary matrix for these findings.

Discussion

Educational technologies possess remarkable potential for enabling and supporting self-regulated learning (SRL) (Azevedo, 2005; Devolder et al., 2012; Winters et al., 2008), but these benefits are contingent upon quality design that aligns with SRL principles and mechanisms. An overarching aim for the current paper was thus to assist developers (and other stakeholders) in quickly assessing technologies and implementations that seek to support SRL. In addition, such a framework might guide documentation of and communication about diverse technologies by offering common terminology along with a systematic means for characterizing systems, their features, and their functions. In service to these goals, we reviewed core aspects of SRL to articulate two overarching design principles for SRL-promoting technologies—the *Platform Principle* and the *Support Principle*—along with a heuristic assessment framework for exploring educational technology design. According to the Platform Principle, SRL-promoting technologies must include specific tools and features for engaging in SRL activities (e.g., planning, enacting, monitoring, and adapting). According to the Support Principle, effective use of SRL platforms must be scaffolded with respect to strategies, metacognition, motivation, and independence. The intertwined demands imposed by these two principles result in potentially complex system designs because there are numerous ways to enable and facilitate SRL. Using the framework, developers and educators can heuristically review technologies for whether key platforms or supports are incorporated and how they are specifically implemented.

The utility of the heuristic assessment framework was demonstrated via an analysis of a prototype version of the PERvasive Learning System (PERLS) (). Application of the framework allowed us to situate the PERLS SRL model within the context of existing conceptions of SRL, and to document how PERLS Version 1.0 addressed elements of planning and enacting phases of SRL while largely neglecting monitoring and adapting. These assessments informed a mapping (see Figs. 2 and 3, and Table 1) of what the technology offered and where there might be gaps to be addressed in further development. In the case of PERLS Version 1, our heuristic assessment drove updates to the learning model and offered guidance for how future versions of PERLS could better support SRL. For example, future PERLS features might add explicit metacognitive prompts (monitoring), enable more flexible goal-setting (planning), combine quiz card functions to develop longer exams (monitoring), improve accessibility of external content (enacting), and leverage flash card functions to target deeper comprehension strategies such as self-questioning or self-testing (enacting and monitoring) that can help to fill knowledge gaps (adapting).

Several of these recommendations are being implemented within iterative versions of PERLS, and PERLS v2.8 has been empirically studied within a US Army training school (Craig et al., 2022a). In that version of PERLS, learners began their journey by using a goal-setting feature. New metacognitive prompts were implemented using "Tip Cards," and "Quiz Card" and "Flash Card" functions were embedded within "Article Cards" that delivered subject matter information. An "External Link" facilitated fast access to external resources, such as supplemental course readings. Finally, a new test feature combined available Quiz Cards into a comprehensive 100-item assessment (i.e., revisiting and reinforcing previous content). Studies on newer versions of PERLS are still ongoing and those findings are not the focus of the current paper. Nonetheless, initial findings appear positive in terms of impact on course performance (Craig et al., 2022b) and self-reported SRL skills (Craig et al., 2022a).

Contributions

The framework presented in this paper offers several contributions with respect to educational technology *assessment*, *design*, *communication*, and *future research*.

Assessment

As a formative assessment framework, our approach directly supports the systematic review of existing or proposed technologies. Importantly, many SRL-promoting technologies are necessarily multifaceted; with so many "moving parts," it can be challenging to determine which features are linked to observed outcomes. The componential nature of the framework helps assessors to operationalize distinct phases of SRL, platforms and tools, types of support, and how they are implemented. Assessments can then be conducted by stakeholders to understand outcomes or investigate whether technologies will fulfill their needs.

For example, designers can assess their own tools to gauge whether self-regulation is sufficiently enabled and scaffolded. Diagnostically, these assessments may explain (or predict) why a given technology is either successful or underperforming (e.g., based on student performance metrics). Relatedly, researchers can use the framework to define and precisely manipulate the presence, absence, or combination of technology features. This process might help researchers avoid confounded experiments that do not permit clear attributions (of either success or failure) to a given feature of interest. From a meta-analytic standpoint, it might also be beneficial to have a concrete and common framework for comparing systems. Thus, although the framework presented here is formative in nature, it may also offer utility for summative evaluations to determine system efficacy.

Beyond system performance, assessments might also extend to comparing and contrasting commercial products—a market analysis. Developers can use the framework to describe current tools with regard to common, uncommon, or neglected platforms and supports. In turn, this mapping may drive competitive innovation by pinpointing where a new technology can fulfill a need in the market. Finally, educators and school administrators might find value in using the framework to determine the most suitable tools to adopt for their classrooms. Educators might first consider their instructional needs (e.g., the self-regulation activities, skills, or strategies that require attention) and then use the framework to select the technologies that will meet those needs. Is a tool needed to support only one or two phases of SRL, or do students need a technology that enables the "complete loop" of self-regulation? The heuristic framework could potentially help educators determine which tools will best align with their pedagogy.

Design

In addition to the assessment of existing technologies, the framework might also guide ideation or development of plans for new technologies. From the earliest stages of design, creators might use the framework to specify *in advance* what SRL platforms and supports will be addressed and what form they will take. The heuristic process can ensure that there are no unintentional gaps (e.g., key components of SRL lack a platform or are unsupported) or that omissions are deliberate, acknowledged, and justified within the scope of the technology. Designers might also begin to map out how combinations of features and tools are intended to work synergistically as learners traverse through "phases" of self-regulation. In combination with persona-based methods in education (Minichello et al., 2018; Salminen et al., 2022), developers might articulate how they imagine learners can use the technology to self-regulate.

As alluded to previously, the design affordances of the framework might be powerfully integrated with a needs assessment to define exactly what stakeholders (e.g., learners, teachers, parents, and school administrators) seek from a given technology. Although we have described a comprehensive model that includes all four "phases" of SRL, educators and learners working in a given context may not need all of these components. For example, some aspects of SRL might already be addressed via the curriculum or other tools. Similarly, stakeholders may identify desires for specific manifestations of platforms or scaffolds. A careful and empathetic needs assessment can thus contribute further guidance or constraints to the heuristic design process, resulting in a more complete map of the technology to be created.

Communication

Another potential contribution of the framework may be to enable or facilitate communication about educational technologies using common language. The underlying principles and constructs of SRL have been articulated in diverse ways across research groups and studies (Panadero, 2017). For instance, in the analysis of PERLS Version 1, it was valuable to "translate" the developers' theoretical model () into more familiar terminology. Various conceptualizations are meaningful and valid, but differing jargon or constructs can impede comparison of technologies. Based on a review of the literature, our framework described four phases (i.e., planning, enacting, monitoring, and adapting) and, perhaps most importantly, established heuristic concepts of "platforms" and "supports" that can ground conversations about technologies. System developers might use the framework to precisely communicate what their product offers and how these functions are achieved. In turn, stakeholders could readily compare and discuss different products side-by-side using the same language and visualizations. Shared terminology and representations can help people identify what different systems offer and how those align to what users need from the tools.

Finally, we argue that the framework can inspire and support future research on self-regulated learning with technology. For example, one proposition informed by the framework is that incorporating platforms for all or most phases may be more effective than enabling only one or two phases. In other words, technologies that allow learners to progress iteratively through all stages of SRL within the system itself—instead of relying upon multiple tools to achieve different SRL goals—may afford better performance. However, a counterproposition also has merit: a suite of technologies or activities working in concert may be just as effective. It may also be more cost effective to integrate multiple existing tools than to attempt to create a single system that "does it all." Indeed, building platforms (or multiple platforms) for every SRL phase would be a monumental undertaking. There is also no good reason why SRL activities cannot be conducted "offline" with other people (e.g., from peer tutors, Roscoe, 2014) instead of technology. It is important to promote the full range of SRL, but this might be achieved by combining multiple approaches. Our framework allows researchers to precisely specify which platforms and supports are present, and in what formats, which in turn supports empirical and unconfounded evaluations of what interventions work "best."

In parallel, another proposition is that offering multiple and diverse scaffolds for SRL platforms will be more effective than fewer or isolated supports. That is, a platform that is accompanied by scaffolds for strategy use and metacognitive processing and motivational engagement and independence may enable better learner performance. However, it may be that certain scaffolds (or categories of scaffolds) are much more impactful given the effort needed to build them. For instance, strategy instruction might be more crucial than motivation if learners require more assistance with "how to learn" than "why to learn." Finally, supports may not need to be offered by a single technology or only via technology. These are testable questions and the framework affords articulating and operationalizing such experimental evaluations.

Potential Extensions of the Framework

Although the current heuristic framework has demonstrated value for assessing educational technologies in an actionable manner, theoretical and applied models of SRL are complex and evolving. Any useful framework should allow for expansion. Along these lines, we briefly consider three areas for potential extensions: *more nuanced dimensions of self-regulation*, *personalization and adaptivity*, and *equity and accessibility*.

First, the current framework incorporated concepts of "metacognition" and "motivation" in fairly general ways, but specific nuances may be meaningful. For instance, we acknowledge that metacognitive monitoring comprises numerous specific actions such as prospective and retrospective judgments (Baars et al., 2014), self-questioning (Joseph et al., 2016), and more. However, the current framework includes a single "metacognition" category that combines such behaviors under one label. Functionally, this may imply that metacognition activities and are interchangeable or equivalent, which is unlikely to be true. Further investigation may highlight whether distinct types of metacognitive supports should be separately represented in the framework. A heuristic assessment may need to examine the presence and implementation of these subclasses independently. Likewise, the sweeping term of "motivation" encompasses very diverse components such as achievement goals (Duffy & Azevedo, 2015), beliefs (Smit et al., 2017), and more that influence learners via different mechanisms. Distinct subclasses of motivational factors may need to be explicated in the framework to enable a more nuanced characterizations of SRL-promoting technologies. Multiple categories of motivation may need to be addressed for a technology to "fully" support this aspect of self-regulation. The most meaningful degree of nuance is another target for potential research.

Second, personalization and adaptivity are increasingly important features for educational technology, such that learning tools provide content, feedback, recommendations, and other data-driven assistance tailored to learners' individual background, behaviors, or goals (Azevedo & Gašević, 2019; Lodge et al., 2018; Tabuenca et al., 2015; Winne, 2018). Indeed, personalized goal-setting and recommendations were a component in the PERLS Version 1 system reviewed in this paper. However, in developing the current heuristic assessment framework, it was unclear whether personalization is *required* for SRL support. Existing evidence attests to the benefits of intelligently adaptive systems, but it may be possible for learners to engage in self-regulation without personalized guidance—generalized prompts or structures may be sufficient. Another consideration is how personalization might best be incorporated into the framework. Personalization could be defined as another dimension of support akin to “strategy support” or “motivational support.” In contrast, personalization might also exist as a third principle—a *Personalization Principle*—that influences the fundamental design of both SRL platforms and supports. Heuristically, stakeholders might consider the extent to which platforms for planning, enactment, monitoring, and adapting are personalized (or not), and might similarly consider whether supports for strategies, metacognition, monitoring, and independence are personalized (or not). The issue of personalized educational technology is also much broader than SRL-promoting tools, and thus perhaps personalization warrants its own design framework.

Finally, a similar question arises with equity and accessibility. Educational technology developers, researchers, and users have considered how technologies participate in (un) fair or (in) equitable learning experiences (Roscoe et al., 2022; see also Universal Design for Learning, Edyburn, 2021; Rogers-Shaw et al., 2017). Differences in technology resources and infrastructure (e.g., reliable networks) can govern who can use an educational technology (e.g., the digital divide, Hohlfeld et al., 2008), and technologies design for or with one population may not generalize to other populations. When developing an SRL-promoting technology, we need to consider *who* is included or excluded from that process, and *who* is included or excluded from using the product. These questions can be framed heuristically (see Cole, 2009, for example) to guide attention and assessment. An empirical research question is whether SRL is measurably promoted by tools that are more equitable, culturally responsive, accessible, and user-friendly. If a technology can nurture a sense of belonging (see Strayhorn, 2018), will learners engage in more or better self-regulation? Importantly, as with personalization, issues of equity and accessibility are not unique to self-regulation; they apply broadly to many educational experiences (see Roscoe, 2022) and may comprise an *Equity Principle* for design. Notably, frameworks for universal design for learning (UDL) already exist and do not need to be subsumed within the current framework.

Conclusion

Researchers and educators have developed a variety of computer-based technologies that can facilitate iterative processes of planning, enacting, monitoring, and adapting—self-regulated learning (SRL)—that drive successful and robust learning. Informed by the SRL literature and related work, this paper articulated two fundamental principles for designing and assessing SRL-promoting technologies: the Platform Principle and the Support Principle. In addition, we provided a straightforward heuristic assessment framework for developers, educators, and other stakeholders to map out how systems implement platforms for self-regulation and support these platforms with regard to strategies, metacognition, motivation, and independence. We argue that the framework offers shared language and structure to that can advance design, communication, and future research in this area. This approach can reveal how and whether SRL needs are met by which tools, and where gap may need to be fill through further development.

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Declarations

Conflict of Interest The authors declare no competing interests.

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